Gedanken Worlds without Higgs

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What the LHC *is not really* for . . .

- Find the Higgs boson,
  the Holy Grail of particle physics,
  the source of all mass in the Universe.
- Celebrate.
- Then particle physics will be over.

We are not ticking off items on a shopping list . . .

We are exploring a vast new terrain
. . . and reaching the Fermi scale

Challenge: Understanding the Everyday World

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

Consider the effects of all the $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ *interactions!*

Modified Standard Model: No Higgs Sector: $\overline{\text{SM}}_1$

$\text{SU(3)}_\text{c} \otimes \text{SU(2)}_\text{L} \otimes \text{U(1)}_Y$ with massless u, d, e, ν

(treat $\text{SU(2)}_\text{L} \otimes \text{U(1)}_Y$ as perturbation)

Nucleon mass little changed:

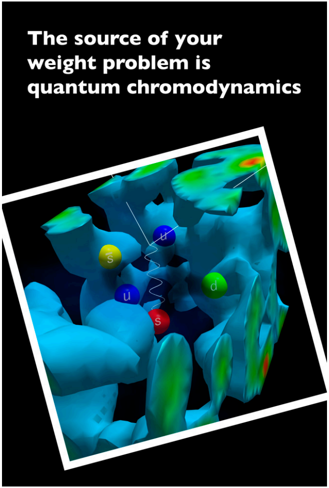
$$M_p = C \cdot \Lambda_{\text{QCD}} + \ldots$$

$$3\,\frac{m_u + m_d}{2} = 10 \pm 2\ \text{MeV}$$

Small contribution from virtual strange quarks

M_N decreases by $< 10\%$ in chiral limit

QCD accounts for (most) visible mass in Universe



(not the Higgs boson)

Modified Standard Model: No Higgs Sector: $\overline{\mathrm{SM}}_1$

QCD has exact $\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R}$ chiral symmetry.

At an energy scale $\sim \Lambda_{\mathrm{QCD}}$, strong interactions become strong, fermion condensates $\langle \bar{q}q \rangle$ appear, and

$$\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R} \rightarrow \mathrm{SU(2)_V}$$

$\rightsquigarrow$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

Fermion condensate . . .

links left-handed, right-handed fermions

$$\langle \bar{q}q \rangle = \langle \bar{q}_{\mathrm{R}} q_{\mathrm{L}} + \bar{q}_{\mathrm{L}} q_{\mathrm{R}} \rangle$$

transforms as $\mathrm{SU}(2)_{\mathrm{L}}$ doublet with $|Y| = 1$

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Broken generators: 3 axial currents; couplings to π: f_π

Turn on $SU(2)_L \otimes U(1)_Y$*:*
Weak bosons couple to axial currents, acquire mass $\sim gf_\pi$

$g \approx 0.65,\ f_\pi = 92.4$ MeV

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{f_\pi^2}{4} \quad (b_1, b_2, b_3, \mathcal{A})$$

same structure as standard EW theory

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Diagonalize:

$$\begin{aligned} M_W^2 &= g^2 f_\pi^2/4 \\ M_Z^2 &= (g^2 + g'^2) f_\pi^2/4 \\ M_A^2 &= 0 \end{aligned}$$

$$M_Z^2/M_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W$$

NGBs become longitudinal components of weak bosons.

$$\boxed{M_W \approx 30 \text{ MeV}}$$

No fermion masses . . .

(Possible division of labor)

Inspiration for Technicolor $\rightsquigarrow$ *Extended Technicolor . . .*

Electroweak scale

EW theory: *choose* $v = (G_\mathrm{F}\sqrt{2})^{-1/2} \approx 246$ GeV

$\overline{\mathrm{SM}}$: *predict*

$$\overline{G}_\mathrm{F} = G_\mathrm{F} \cdot (v^2/\bar{f}_\pi^2) \approx 8 \times 10^6\, G_\mathrm{F} \approx 93.25\ \mathrm{GeV}^{-2}$$

Scale cross sections by $(\overline{G}_\mathrm{F}/G_\mathrm{F})^2 \approx 6.4 \times 10^{13}$

Four-fermion partial-wave unitarity breaks down at
$E_\mathrm{cm} \approx 600\ \mathrm{GeV} \cdot (\bar{f}_\pi/v) \approx 215$ MeV in $\overline{\mathrm{SM}}$.

$\bar{f}_\pi \approx 0.94 f_\pi \approx 87$ MeV

Consistent with $\overline{M}_W = 28$ MeV

$\overline{\mathrm{SM}}_1$: Hadron Spectrum

Pions absent (became longitudinal $W^{\pm}$, Z^0)

ρ, ω, a_1 "as usual"

Δ above N

Nucleon mass little changed: look in detail

Nucleon masses ...

"Obvious" that proton should outweigh neutron

... but false in real world: $M_n - M_p \approx 1.293$ MeV

SU(6) flavor-spin wave functions,

$$\begin{aligned} |p\uparrow\rangle &= (1/\sqrt{18})\,(2u_\uparrow d_\downarrow u_\uparrow - u_\downarrow d_\uparrow u_\uparrow - u_\uparrow d_\uparrow u_\downarrow \\ &\quad - d_\uparrow u_\downarrow u_\uparrow + 2d_\downarrow u_\uparrow u_\uparrow - d_\uparrow u_\uparrow u_\downarrow \\ &\quad - u_\uparrow u_\downarrow d_\uparrow - u_\downarrow u_\uparrow d_\uparrow + 2u_\uparrow u_\uparrow d_\downarrow)\,, \\ |n\uparrow\rangle &= -(1/\sqrt{18})\,(2d_\uparrow u_\downarrow d_\uparrow - d_\downarrow u_\uparrow d_\uparrow - d_\uparrow u_\uparrow d_\downarrow \\ &\quad - u_\uparrow d_\downarrow d_\uparrow + 2u_\downarrow d_\uparrow d_\uparrow - u_\uparrow d_\uparrow d_\downarrow \\ &\quad - d_\uparrow d_\downarrow u_\uparrow - d_\downarrow d_\uparrow u_\uparrow + 2d_\uparrow d_\uparrow u_\downarrow)\,, \end{aligned}$$

Nucleon masses . . .

Simple quark model:

$$
\begin{aligned}
M &= M_0 + n_d(m_d - m_u) + \left\langle \frac{\alpha}{r} \right\rangle \sum_{i<j} e_i e_j \\
&\quad - \frac{8\pi}{3} \left|\Psi_{ij}(0)\right|^2 \left\langle \sum_{i<j} \mu_i \mu_j \, \vec{\sigma}_i \cdot \vec{\sigma}_j \right\rangle \; .
\end{aligned}
$$

$$
\begin{aligned}
M &= M_0 + n_d(m_d - m_u) + \delta M_{\mathrm{C}} \sum_{i<j} e_i e_j \\
&\quad + \delta M_{\mathrm{M}} \left\langle \sum_{i<j} e_i e_j \, \vec{\sigma}_i \cdot \vec{\sigma}_j \right\rangle \; ,
\end{aligned}
$$

Nucleon masses . . .

$$M_p = M_0 + (m_d - m_u) \qquad\qquad + \tfrac{4}{3}\delta M_{\mathrm{M}}$$

$$M_n = M_0 + 2(m_d - m_u) - \tfrac{1}{3}\delta M_{\mathrm{C}} + \delta M_{\mathrm{M}}$$

$$M_n - M_p = (m_d - m_u) - \tfrac{1}{3}\delta M_{\mathrm{C}} - \tfrac{1}{3}\delta M_{\mathrm{M}}.$$

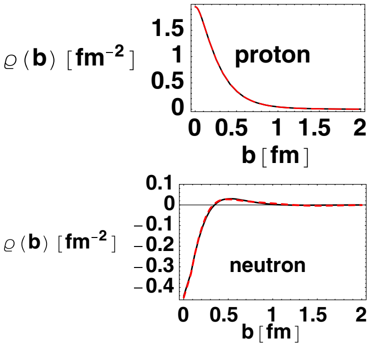
In $\overline{\mathrm{SM}}$, proton would outweigh neutron,

$$\overline{M}_n - \overline{M}_p = -\tfrac{1}{3}\delta M_{\mathrm{C}} - \tfrac{1}{3}\delta M_{\mathrm{M}} \approx -1.7\ \mathrm{MeV},$$

. . . but weak contributions enter.

Aside: Better control of EM contributions soon?

New measurements of *n* and *p* form factors at JLAB

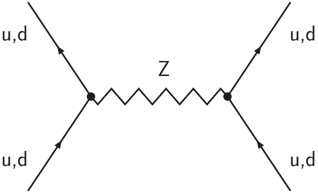


G. Miller, PRL 99, 112001 (2007)

G_E, G_M determinations should soon allow more accurate evaluation of Born terms in the Cottingham formula

Weak contributions are not negligible

$$\overline{M}_n - \overline{M}_p\big|_{\text{weak}} \propto dd - uu$$



$$\begin{aligned}\overline{M}_n - \overline{M}_p\big|_{\text{weak}} &= \frac{\overline{G}_{\mathrm{F}}\Lambda_{\mathrm{h}}^3\sqrt{2}}{3}x_{\mathrm{W}}(1-2x_{\mathrm{W}}) \approx \frac{\overline{G}_{\mathrm{F}}\Lambda_{\mathrm{h}}^3\sqrt{2}}{24} \\ &= \frac{\Lambda_{\mathrm{h}}^3}{3\bar{f}_\pi^2}x_{\mathrm{W}}(1-2x_{\mathrm{W}}) \approx \frac{\Lambda_{\mathrm{h}}^3}{24\bar{f}_\pi^2} > 0\end{aligned}$$

$x_{\mathrm{W}} = sin^2\theta_{\mathrm{W}} \approx \frac{1}{4}$

perhaps a few MeV?

Bending the rules . . .

$$\left.\overline{M}_n - \overline{M}_p\right|_{\text{weak}} \text{ doesn't depend on } g$$

(in point-coupling limit)

$$\left.\overline{M}_n - \overline{M}_p\right|_{\text{em}} \propto \alpha \propto g^2 x_{\text{W}}$$

Amusing that (for fixed x_{W})
increasing or decreasing g
increases or decreases em with respect to weak

Consequences for β decay

Scale decay rate $\Gamma \sim \overline{G}_{\mathrm{F}}^{2}|\overline{\Delta M}|^{5}/192\pi^{3}$ (rapid!)

$$n \longrightarrow p e^{-} \bar{\nu}_e \text{ or } p \longrightarrow n e^{+} \nu_e$$

Example: $\overline{M}_p - \overline{M}_n = M_n - M_p \rightsquigarrow \bar{\tau}_p \approx 14$ ps

$\boxed{\text{No Hydrogen Atom}}$

Neutron could be lightest nucleus

Strong coupling in $\overline{\text{SM}}$

In SM, Higgs boson regulates high-energy behavior

Gedanken experiment: scattering of

$$W_L^+ W_L^- \quad \frac{Z_L^0 Z_L^0}{\sqrt{2}} \quad \frac{HH}{\sqrt{2}} \quad HZ_L^0$$

In high-energy limit, s-wave amplitudes

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix} .$$

Strong coupling in $\overline{\mathrm{SM}}$

In *standard model,* $|a_0| \leq 1$ yields

$$M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 4v\sqrt{\pi/3} = 1\ \mathrm{TeV}$$

In $\overline{\mathrm{SM}}_1$ *Gedanken* world,

$$\overline{M}_H \leq \left(\frac{8\pi\sqrt{2}}{3\overline{G}_F}\right)^{1/2} = 4\bar{f}_\pi\sqrt{\pi/3} \approx 350\ \mathrm{MeV}$$

violated because no Higgs boson $\rightsquigarrow$ strong scattering

Strong coupling in $\overline{\text{SM}}$

SM with (very) heavy Higgs boson:

s-wave W^+W^-, Z^0Z^0 scattering as $s \gg M_W^2, M_Z^2$:

$$a_0 = \frac{s}{32\pi v^2}\begin{bmatrix} 1 & \sqrt{2} \\ \sqrt{2} & 0 \end{bmatrix}$$

Largest eigenvalue: $a_0^{\text{max}} = s/16\pi v^2$

$$|a_0| \leq 1 \Rightarrow \sqrt{s^\star} = 4\sqrt{\pi}v \approx 1.74 \text{ TeV}$$

$$\boxed{\overline{\text{SM}}\text{: } \sqrt{s^\star} = 4\sqrt{\pi}\bar{f}_\pi \approx 620 \text{ MeV}}$$

$\overline{\text{SM}}$ becomes strongly coupled on the hadronic scale

Strong coupling in $\overline{\text{SM}}$

As in standard model . . .

$I = 0$, $J = 0$ and $I = 1$, $J = 1$: attractive
$I = 2$, $J = 0$: repulsive

As partial-wave amplitudes approach bounds,
WW, WZ, ZZ resonances form,
multiple production of W and Z

in emulation of $\pi\pi$ scattering approaching 1 GeV

Detailed projections depend on unitarization protocol

What about atoms?

Suppose some light elements produced in BBN survive

Massless $e \Longrightarrow \infty$ Bohr radius

No meaningful atoms

No valence bonding

No integrity of matter, no stable structures

Strong-interaction symmetries

- ▷ Strong CP problem: $\mathcal{L}_\theta = \dfrac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$
  can be tuned away if at least one $m_q = 0$

- ▷ Real world: strong interactions respect P & C
  Gedanken world: long-range "strong" interactions from W, Z exchange (no pions) so P & C are violated

Look more closely at NN interaction in $\overline{\mathrm{SM}}_1$

Nuclear force in the *Gedanken* world

- Size of hadrons:
  $1/m_\pi \approx 1.4$ fm in real world
  $1/\overline{M}_W \approx 7$ fm in $\overline{\mathrm{SM}}_1$

- π-exchange in real world

$$A(N_1 N_2 \to N_3 N_4) \sim \frac{g_{\pi NN}^2}{m_\pi^2} \qquad g_{\pi NN} \approx 14$$

  W-exchange in *Gedanken* world

$$\overline{A}(N_1 N_2 \to N_3 N_4) \sim \frac{g^2}{8\overline{M}_W^2} \sim \frac{1}{2\overline{f}_\pi^2}$$

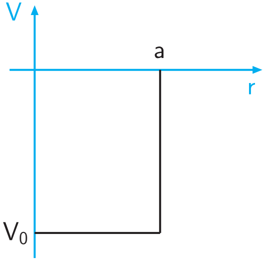
Nuclear force in the *Gedanken* world

- ▷ *NN* scattering amplitude smaller in $\overline{\mathrm{SM}}_1$:

$$\bar{A}/A = \frac{m_\pi^2}{2\bar{f}_\pi^2 g_{\pi NN}^2} = 0.0065$$

but (as we saw) 5× longer range

- ▷ Bound states as $\xi = 2\mu V_0 a^2/\hbar^2\pi^2 \sim O(1)$



(μ: reduced mass)

$$\frac{\bar{\xi}}{\xi} = \frac{m_\pi^2}{2\bar{f}_\pi^2 g_{\pi NN}^2} \cdot \frac{m_\pi^2}{\overline{M}_W^2} \approx \frac{1}{6}$$

Not $\ll 1$

Weak interactions in $\overline{\text{SM}}_1$

Real world:

$$\sigma_{\text{tot}}(\nu_\mu N)/E_\nu = (0.677 \pm 0.014) \times 10^{-38}\ \text{cm}^2\ \text{GeV}^{-1}$$

$E_\nu \sim 30 - 200$ GeV

Scaling by $(\overline{G}_{\text{F}}/G_{\text{F}})^2 = 6.4 \times 10^{13} \rightsquigarrow$

$$\overline{\sigma}_{\text{tot}}(\nu_e N)/E_\nu \approx 435\ \text{mb GeV}^{-1}$$

(point-coupling limit)

W-propagator damps at $E_\nu \approx 4$ MeV

Rough estimate: $\overline{\sigma}_{\text{tot}}(\nu_e N) \sim 1$ mb

EWSB with $n_g > 1$ fermion generations: $\overline{\mathrm{SM}}_{n_g}$

Spontaneously broken $\mathrm{SU}(n_g)_\mathrm{L} \otimes \mathrm{SU}(n_g)_\mathrm{R} \to \mathrm{SU}(n_g)_\mathrm{V}$

$$
\begin{aligned}
|\Pi^+\rangle &= \frac{1}{\sqrt{n_g}} \textstyle\sum_{i=1}^{n_g} |u_i \bar{d}_i\rangle \\
|\Pi^0\rangle &= \frac{1}{\sqrt{2n_g}} \textstyle\sum_{i=1}^{n_g} |(u_i \bar{u}_i - d_i \bar{d}_i)\rangle \\
|\Pi^-\rangle &= \frac{1}{\sqrt{n_g}} \textstyle\sum_{i=1}^{n_g} |d_i \bar{u}_i\rangle .
\end{aligned}
$$

3 of $(4n_g^2 - 1)$ NGBs

$$\overline{M}_W^2 = n_g\, g^2 \bar{f}_\pi^2/4 \quad \overline{M}_Z^2 = n_g (g^2 + g'^2)\bar{f}_\pi^2/4 \quad \overline{G}_\mathrm{F} \propto 1/n_g$$

so $\sqrt{s^\star} = 4\sqrt{\pi n_g}\bar{f}_\pi \approx 620\sqrt{n_g}$ MeV

Meson spectrum in $\overline{\mathrm{SM}}_{n_g}$

n_g^2 NGBs each with charge ± 1

$\sim$ real-world $\pi^\pm$ ($n_g = 1$); & $K^\pm$, $D^\pm$, $D_s^\pm$ ($n_g = 2$)

$2n_g(n_g - 1)$ charge-zero NGBs with flavor

$\sim K^0, \bar{K}^0$, and $D^0, \bar{D}^0$ ($n_g = 2$)

$2n_g - 1$ self-conjugate flavor-nonsinglet NGBs

$\sim \pi^0$ ($n_g = 1$); & η and η_c ($n_g = 2$)

After EWSB, $4n_g^2 - 4$ NGBs

$\rightsquigarrow$ very large hadrons, very long range nuclear forces

Goldberger–Treiman: $|g_A|\, M_N = f_\pi g_{\pi NN}$

Baryon spectrum in $\overline{\mathrm{SM}}_{n_g}$

Similar to real-world spectrum ...

$$\mathbf{n_q} \otimes \mathbf{n_q} \otimes \mathbf{n_q} = S_3 \oplus M_1 \oplus M_2 \oplus A_3$$

$$\begin{aligned} \dim(S_3) &= \frac{n_q(n_q+1)(n_q+2)}{3!} \\ \dim(M) &= \frac{n_q(n_q^2-1)}{3} \\ \dim(A_3) &= \binom{n_q}{3} \end{aligned}$$

$\mathrm{SU}(2n_g)_{\mathrm{flavor}}$ symmetry exact

equal masses within multiplets

Massless fermion pathologies . . .

Vacuum readily breaks down to e^+e^- plasma

. . . persists with GUT-induced tiny masses

"hard" fermion masses: explicit $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ breaking

NGBs $\longrightarrow$ pNGBs

$$\mathrm{SM}m\text{: } a_J(f\bar{f} \to W_L^+ W_L^-) \propto G_\mathrm{F} m_f E_\mathrm{cm}$$

saturate p.w. unitarity at

$$E_f \simeq \frac{4\pi\sqrt{2}}{\sqrt{3\eta_f}\, G_\mathrm{F} m_f} = \frac{8\pi v^2}{\sqrt{3\eta_f}\, m_f}$$

$\eta_f = 1(N_\mathrm{c})$ for leptons (quarks)

$\overline{\mathrm{SM}}m$ ...

Add explicit fermion masses to $\overline{\mathrm{SM}}$

$a_J(f\bar{f} \to W_L^+ W_L^-)$ unitarity respected up to
$\sqrt{s^\star} = 4\sqrt{\pi n_g}\bar{f}_\pi \approx 620\sqrt{n_g}$ MeV
(condition from WW scattering)

$$\rightsquigarrow m_f \lesssim \frac{2\sqrt{\pi n_g}\bar{f}_\pi}{\sqrt{3\eta_f}} \approx \begin{cases} 126\,\sqrt{n_g}\ \text{MeV (leptons)} \\ 73\,\sqrt{n_g}\ \text{MeV (quarks)} \end{cases}$$

would accommodate real-world e, u, d masses

Extension to $N_c > 3$

EWSB scale is related to QCD confinement scale in $\overline{\text{SM}}$

Examine N_c scaling laws, $N_c \to \infty$ limit

QCD: hold $g_3^2 N_c =$ constant as $N_c \to \infty$

Anomaly freedom fixes quark charges:

$$e_u = e_d + 1 = \tfrac{1}{2}\left[1 - (2e_e + 1)/N_c\right]$$

$SU(2)_L \otimes U(1)_Y$: $g^2 N_c,\ g'^2 N_c,\ e^2 N_c \to$ fixed as $N_c \to \infty$

…compensates $f_\pi \propto \sqrt{N_c}$

$\overline{M}_W$ independent of N_c, so $\overline{G}_F \propto 1/\sqrt{N_c}$

In summary . . .

- $\overline{\mathrm{SM}}$: QCD-induced $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \to \mathrm{U(1)_{em}}$
- No fermion masses; division of labor?
- No physical pions in $\overline{\mathrm{SM}}_1$
- No quark masses: proton outweighs neutron ?
- Infinitesimal m_e: integrity of matter compromised
- $\overline{\mathrm{SM}}$ exhibits strong W, Z dynamics below 1 GeV
- $\overline{M}_W \approx 30$ MeV in *Gedanken* world
- $\overline{G}_\mathrm{F} \sim 10^7\, G_\mathrm{F}$: accelerates β decay
- Weak, hadronic int. comparable; nuclear forces
- Infinitesimal m_ℓ: vacuum breakdown, e^+e^- plasma
- $\overline{\mathrm{SM}}m$: effective theory through hadronic scale

Outlook

How different a world, without a Higgs mechanism:
preparation for interpreting LHC insights

$\overline{\mathrm{SM}}$ an explicit theoretical laboratory
complement to studies that retain Higgs, vary *v*
(very intricate alternative realities)

fresh look at the way we have understood the real world
(possibility of > 1 source of SSB)

How might EWSB deviate from the Higgs mechanism?